

Transverse momentum and pseudorapidity dependences of '*Mach-like*' correlations for central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV

S. Zhang,^{1,2} G. L. Ma,¹ Y. G. Ma,^{1,*} X. Z. Cai,¹ J. H. Chen,^{1,2} H. Z. Huang,³
W. Q. Shen,¹ X. H. Shi,^{1,2} F. Jin,^{1,2} J. Tian,^{1,2} C. Zhong,¹ and J. X. Zuo^{1,2}

¹Shanghai Institute of Applied Physics, Chinese Academy of Sciences, P.O. Box 800-204, Shanghai 201800, China

²Graduate School of the Chinese Academy of Sciences, Beijing 100080, China

³Dept of Physics and Astronomy, University of California at Los Angeles, CA 90095, USA

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The transverse momentum and pseudorapidity dependences of partonic '*Mach-like*' shock wave have been studied by using a multi-phase transport model (AMPT) with both partonic and hadronic interactions. The splitting parameter D , i.e. half distance between two splitting peaks on away side in di-hadron azimuthal angular ($\Delta\phi$) correlations, slightly increases with the transverse momentum of associated hadrons (p_T^{assoc}), which is consistent with preliminary experimental trend, owing to different interaction-lengths/numbers between wave partons and medium in strong parton cascade. On the other hand, the splitting parameter D as a function of pseudorapidity of associated hadrons (η^{assoc}), keeps flat in mid-pseudorapidity region and rapidly drops in high-pseudorapidity region, which is as a result of different violent degrees of jet-medium interactions in the medium that has different energy densities in the longitudinal direction. It is proposed that the research on the properties of '*Mach-like*' correlation can shed light on the knowledge of both partonic and hadronic interactions at RHIC.

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An exotic matter predicted by Quantum Chromodynamics (QCD) [1] may be created in the early stage of central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV at the Relativistic Heavy-Ion Collider (RHIC) at the Brookhaven National Laboratory [2]. The sufficient experimental evidences [3, 4, 5, 6] support that the new matter is not an ideal gas but a strongly-interacting dense partonic matter (named as sQGP) under extreme temperature and energy density.

Jet has been proved to be a good probe to investigate the characters of new matter in RHIC experiments [6]. Calculations based on pQCD predicted that high energy partons (jets) traversing a dense QCD medium lose energy through induced gluon radiation [7], where the energy loss is expected to depend strongly on the color charge density of the created system and the traversed path length of the propagating jets. The energy loss phenomenon (i.e. jet quenching) has been observed by some experimental probes. In di-jet azimuthal angular ($\Delta\phi$) correlations, one back-to-back hard jet disappears due to large energy loss in the dense medium [8]. According to the conservation law of energy, the lost energy should be redistributed in the medium [9, 10, 11, 12], which has been reconstructed by di-hadron azimuthal angular correlations of charged particles in experiments [13]. Recently, an interesting '*Mach-like*' structure (the splitting of the away side peak in di-hadron $\Delta\phi$ correlation) has been observed in both di-hadron and three-hadron az-

imuthal angular correlations in central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV [14, 15, 16], which is attracting many theorists' attentions.

Recently considerable theoretical efforts have been put into the topic [17, 18, 19, 20, 21]. Among these researches, the transverse momentum (p_T) and pseudorapidity (η) dependences of '*Mach-like*' structure are two subjects of much concern. Cherenkov-like gluon radiation model has been suggested to produce a conical structure [18]. It gave the dispersion relations for different choices of masses of two massive scalars coupled to a massless scalar. The dispersion relations are space-like in low momentum and approaches the light cone as momentum is increased. With the dispersion relations, the cone angle with respect to the jet direction becomes narrow rapidly with the increasing of the momentum of the emitted particle. The medium-induced gluon bremsstrahlung radiation [19, 20] has been used to study the di-hadron correlations. In Ref [19], the large angle medium-induced gluon radiation, gave a picture of the radiative angle relative to the jet axis becoming narrow with the increasing of radiative gluon energy, but did not show a two-peak structure on away side. In Ref [20], a simple generalization of Sudakov form factor to opaque media presented non-Gaussian shapes of away-side in di-hadron azimuthal correlations and a centrality dependence of the position of splitting peaks which can match experimental data well. However, there are no discussions about the p_T dependence of non-Gaussian shape in the model. In a shock-wave model proposed by Shuryak and his collaborators [17], linearized hydrodynamic equations were solved in a region far from the jet where the perturba-

*Corresponding author: Email: ygma@sinap.ac.cn

tions and gradients are small. In general, the strength of the diffusion mode relative to the sound mode is directly proportional to the entropy produced by jet-medium interactions. Only when there is no significant entropy produced by strong jet-medium interactions, hydrodynamic fields can be induced and peaks at the Mach angle in di-hadron azimuthal angular correlations can be revealed. It is noticeable that the results are very sensitive to the parameters chosen, especially need very large values for the energy loss to produce the correlation functions similar to the experimental results. The position of the peak on away side, which corresponds to splitting parameter D (the half distance between two peaks on away side in a di-hadron azimuthal angular correlation), is related to the speed of sound c_s . The value of c_s used in the calculation is a time-weighted average ($\bar{c}_s \approx 0.33$) consistent with the expected value for RHIC. As a result, the positions of the peaks at away side are located at $\Delta\phi = \pi \pm \arccos(\bar{c}_s) \approx 1.9, 4.3$ (rad) and no p_T dependence. On the other hand, a probable image of ‘*Mach-cone*’ shock wave was given as a function of rapidity [22], which implied that the splitting parameter D should become smaller with the increasing of the rapidity (y), arising from a folding of condition possibility $p(y)$ and rapidity structure of ‘*Mach-cone*’ correlation. In our previous works, we have shown a partonic ‘*Mach-like*’ shock wave can be produced and evolved in strong parton cascade, developed by hadronic rescattering, in two- and three-particle azimuthal correlation analysis [23, 24, 25]. In this work, we report a study of p_T and η dependences of partonic ‘*Mach-like*’ shock waves by using A Multi-Phase Transport model (AMPT) [26]. The p_T dependence of splitting parameter (D) that D increases with p_T^{asso} slightly is attributed to different interaction-lengths/numbers between wave partons and medium in strong parton cascade and η dependence of splitting parameter (D) that D keeps flat in mid-pseudorapidity and drops quickly in high-pseudorapidity is due to different strengths of jet-medium interactions in the medium which has different energy densities in the longitudinal direction.

AMPT model [26] is a hybrid model which consists of four main components: the initial conditions, partonic interactions, the conversion from partonic matter to hadronic matter and hadronic rescattering. The initial conditions, which include the spatial and momentum distributions of minijet partons and soft string excitations, are obtained from the HIJING model [27]. Excitations of strings melt strings into partons in the AMPT version with string melting mechanism [28] (abbr. ‘*the melting AMPT model*’). Scatterings among partons are modelled by Zhang’s Parton Cascade model (ZPC) [29], which at present only includes two-body scatterings with cross sections obtained from the pQCD calculations with screening mass. In the default version of AMPT model [30] (abbr. ‘*the default AMPT model*’), minijet partons are recombined with their parent strings when they stop interactions, and the resulting strings are converted to hadrons by using the Lund string fragmen-

tation model [31]. In the melting AMPT model, a simple quark coalescence model is used to combine all partons into hadrons. Dynamics of the subsequent hadronic matter is then described by A Relativistic Transport (ART) model [32]. Details of the AMPT model can be found in a recent review [26]. Previous studies have shown that the partonic effect could not be neglected and the melting AMPT model is much more appropriate than the default AMPT model when the energy density is much higher than the critical density for the predicted phase transition [26, 28, 33]. In the present work, the parton interaction cross section in the melting AMPT model is assumed to be 10 mb.

Our analysis in this paper are based on di-hadron azimuthal angular correlations between a high p_T hadron (trigger hadron) and low p_T ones (associated hadrons). The analysis method is similar to that the experimenters did [13, 15]. The pairs of associated and trigger particles in the same events were accumulated to obtain $\Delta\phi = \phi_{assoc} - \phi_{trig}$ distributions. Mixing-event technique was applied to construct background which is expected mainly from elliptic flow [13, 15]. In this method, we mixed two events which have very close centralities into a new mixing event, and obtained $\Delta\phi$ distribution which is regarded as the corresponding background. A Zero Yield At Minimum (ZYAM) assumption was adopted to subtract the background as did in experimental analysis [15] (See Ref. [23] for our detailed analysis techniques). In this work, we took two sets of AMPT models (the *default* and *melting* AMPT models) to simulate the central Au+Au collisions (0-10%) at $\sqrt{s_{NN}} = 200$ GeV. The p_T window cuts for trigger and associated particles are $3 < p_T^{trig} < 4$ GeV/c and $0 < p_T^{assoc} < 3$ GeV/c within pseudorapidity window $|\eta^{trig,assoc}| < 1$ for p_T dependence analysis, and $2.5 < p_T^{trig} < 6$ GeV/c and $1 < p_T^{assoc} < 2.5$ GeV/c within pseudorapidity window $|\eta^{trig}| < 1$ for η^{assoc} dependence analysis.

Figure 1 shows p_T^{assoc} dependences of splitting parameter D in Au + Au collisions (0-10%) at $\sqrt{s_{NN}} = 200$ GeV in the melting and default AMPT model with/without hadronic rescattering (i.e. ART process). Here the trigger and associated particles are with $3 < p_T^{trig} < 4$ GeV/c and $0 < p_T^{assoc} < 3$ GeV/c respectively, both within pseudorapidity window $|\eta^{trig,assoc}| < 1$. There is no significant difference of splitting parameter D between the cases with and without hadronic rescattering in the melting AMPT model, but D in the default AMPT model is smaller than that in the melting AMPT model. It is consistent with our previous results [23] in which hadronic rescattering alone gives much smaller splitting amplitudes than that in the melting AMPT model which shows good D values matching experimental data. Here the melting AMPT model gives much better splitting parameters D which are consistent with the preliminary experimental trend [34], but different from the calculations of Casalderrey-Solana et al. [17] and Koch et al. [18]. It is noticeable that the p_T^{assoc} dependence of splitting pa-

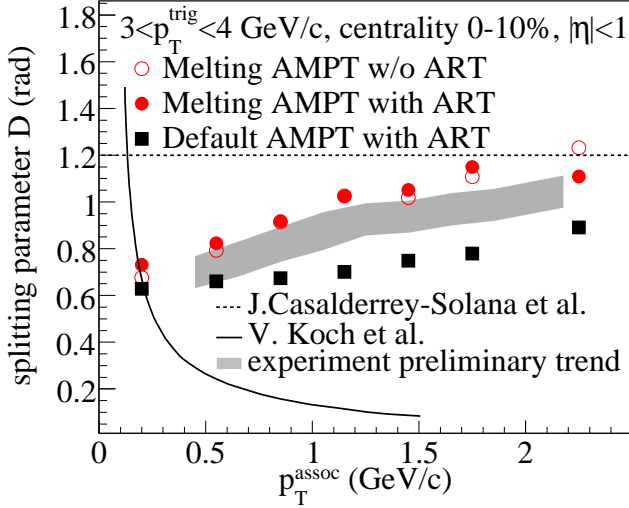


FIG. 1: (Color online) The splitting parameter D as a function of p_T^{assoc} for trigger hadrons of $3 < p_T^{trig} < 4 \text{ GeV/c}$ from AMPT simulations for Au + Au collisions (0-10%) at $\sqrt{s_{NN}} = 200 \text{ GeV}$. Full circles: the melting AMPT model with hadronic rescattering (i.e. ART process); open circles: the melting AMPT model without hadronic rescattering; full squares: the default AMPT model with hadronic rescattering; band: preliminary experimental trend [34].

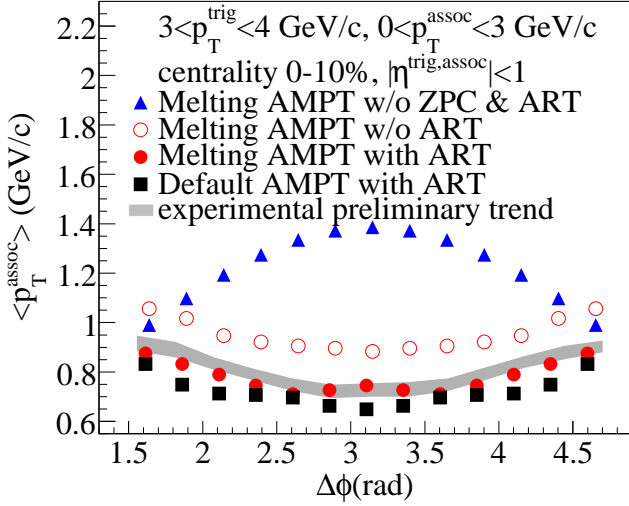


FIG. 2: (Color online) AMPT model calculations of $\langle p_T^{assoc} \rangle$ versus $\Delta\phi$ for away side in di-hadron $\Delta\phi$ correlations with p_T window cut ($3 < p_T^{trig} < 4 \text{ GeV/c}$ and $0 < p_T^{assoc} < 3 \text{ GeV/c}$) in Au + Au collisions (0-10%) at $\sqrt{s_{NN}} = 200 \text{ GeV}$. Full circles: the melting AMPT model with hadronic rescattering; open circles: the melting AMPT model without hadronic rescattering; full triangles: the melting AMPT model without parton cascade (i.e. ZPC process) and hadronic rescattering; full squares: the default AMPT model with hadronic rescattering; band: preliminary experimental trend [34].

parameter D is sensitive to parton cascade (Note that it was found that more long-lived partonic phase and bigger parton interaction cross section can give more bigger D values in our previous work [25].), but not to hadronic rescattering in the melting AMPT model. Therefore, the relation of D vs. p_T^{assoc} can be a good probe that not

only distinguishes different physical scenarios but also sheds light on the properties of partonic interactions in the early stage of the relativistic heavy ion collisions.

Figure 2 presents the relation of average transverse momentum of associated particles ($\langle p_T^{assoc} \rangle \equiv \frac{\sum_i N_i^{assoc} p_{T,i}^{assoc}}{\sum_i N_i^{assoc}}$) versus $\Delta\phi$ for away side. There is a distinct dip structure at $\Delta\phi = \pi$ for all model conditions except the melting AMPT model without parton cascade and hadronic rescattering, which indicates that away jets are depleted by strong parton cascade in the melting AMPT model (or by hadronic rescattering in the default model) and its lost energy is expected to excite the formation of partonic (or hadronic) ‘Mach-like’ shock waves [25]. It is apparent that hadronic rescattering can soften the associated hadrons by comparing the results between with and without hadronic rescattering in the melting AMPT model. The depletion structure implies that harder associated hadrons prefer larger angles with respect to the away-jet direction, which results in the increasing trend of splitting parameter vs p_T^{assoc} as shown in Figure 1. In order to explain the dip structure, we make a simple MC simulation. Figure 3 gives the initial parton number density which is projected into $x - y$ plane in the melting AMPT model. Once shock wave is generated at some points $p(x_0, y_0)$, the wave-front direction would be symmetrical with respect to the away-jet direction (at $\Delta\phi = \pi \text{ rad}$). The average interaction-lengths/numbers of wave-front partons interacting with the medium are with maximums at $\Delta\phi = \pi \text{ rad}$ (i.e. in the away-jet direction), as shown in panel (a) and (b) of Figure 4, which is the cause of the dip structure of $\langle p_T^{assoc} \rangle$ vs $\Delta\phi$ for away side. Though $\langle p_T^{assoc} \rangle$ vs. $\Delta\phi$ in the final state is a result of both parton cascade and hadronic rescattering in the melting AMPT model, it is interesting that a combination research between $\langle p_T^{assoc} \rangle$ vs $\Delta\phi$ and D vs. p_T^{assoc} may provide a potential tool to extract the respective information from two different interaction levels (i.e. partonic and hadronic stages).

As we have already shown that the origin of partonic ‘Mach-like’ shock waves could be attributed to the big partonic interaction cross section which can couple partons together to show a hydro-like collective behavior in our previous papers [24, 25], and our used model is a MC dynamical partonic transport model which can harmoniously work in the regions close to and far from jet, whereas linear hydrodynamical approximation is only applicable in the region far from jet as discussed above. Therefore, it is not strange that such an increasing dependence, which is different from the predicted by a hydrodynamic calculation [17], is presented in the present model.

In the above studies on p_T dependences of D , both the trigger and associated hadron both are located at mid-pseudorapidity ($|\eta^{trig,assoc}| < 1$). When one scans the whole pseudorapidity region to look for all hadrons which are associated with a mid-pseudorapidity trigger hadron, how about the associated hadrons in other pseudorapid-

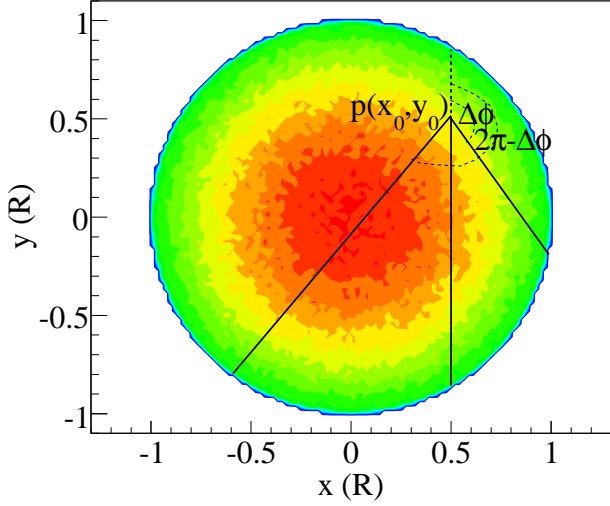


FIG. 3: (Color online) The initial distribution of parton number density in mid-rapidity for Au + Au collisions (0-10%) at $\sqrt{s_{NN}} = 200$ GeV in the melting AMPT model, which has been projected into x-y plane, where $p(x_0, y_0)$ is the generation point of Mach-like shock wave and R is the scale size of the system.

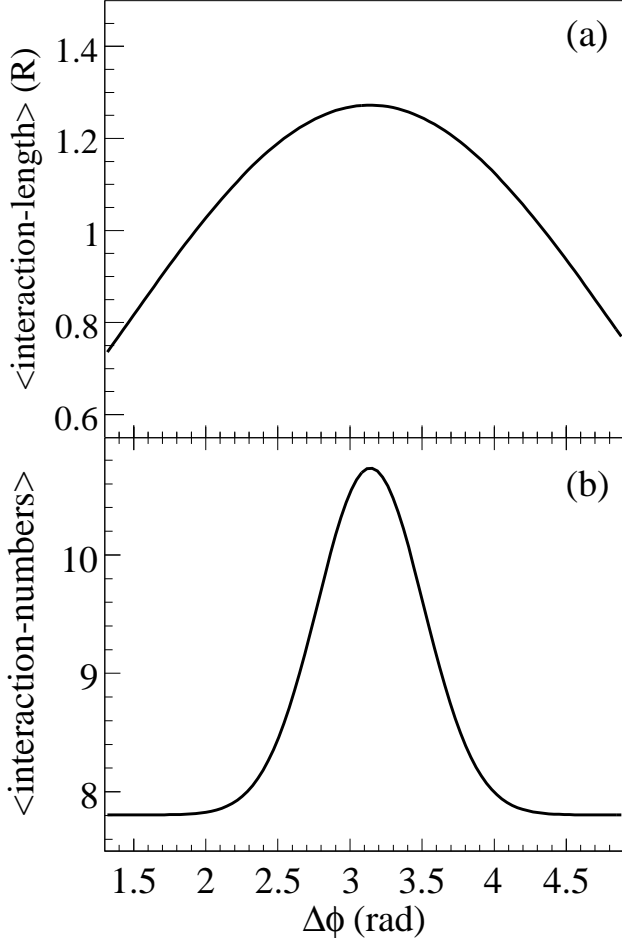


FIG. 4: (a): The average interaction-lengths of a wave parton undergoing the medium in different $\Delta\phi$; (b): The average interaction-numbers of a wave parton undergoing the medium in different $\Delta\phi$ for Au + Au collisions (0-10%) at $\sqrt{s_{NN}} = 200$ GeV in the melting AMPT model.

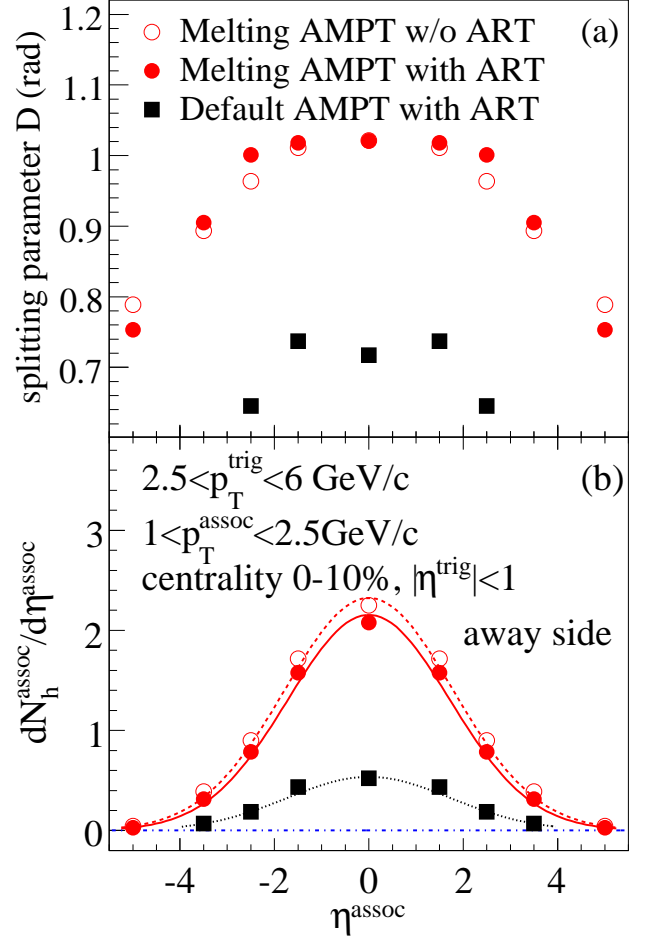


FIG. 5: (Color online) The AMPT model calculations in Au + Au collisions (0-10%) at $\sqrt{s_{NN}} = 200$ GeV. (model cuts: $2.5 < p_T^{trig} < 6$ GeV/c, $1 < p_T^{assoc} < 2.5$ GeV/c, and $|\eta^{trig}| < 1$). (a): the pseudorapidity dependences of splitting parameter D ; (b): the pseudorapidity distributions of associated hadron yields for away side. Full circles: the melting AMPT model with hadronic rescattering (i.e. ART process); open circles: the melting AMPT model without hadronic rescattering; full square: the default AMPT model with hadronic rescattering; lines: the corresponding Gaussian fitting functions.

ity regions? Are they waked by an away-jet? Figure 5 (a) shows the dependences of splitting parameter D on the pseudorapidity of associated hadrons (η^{assoc}), for a given trigger hadron within $|\eta^{trig}| < 1$. The splitting parameter D is almost unchanged in a wide mid-pseudorapidity region, but goes down quickly at high absolute value of pseudorapidity. For the splitting parameter D in the default AMPT model with hadronic rescattering, it is lower than that in the melting AMPT model and not comparable with experimental results, which further demonstrates that strong parton cascade process is necessary for reproducing reasonable splitting parameters. Figure 5 (b) gives pseudorapidity distributions of associated hadron yields for away side with a trigger hadron in mid-pseudorapidity. The associated yield on away side in the melting AMPT model is higher than that in the default

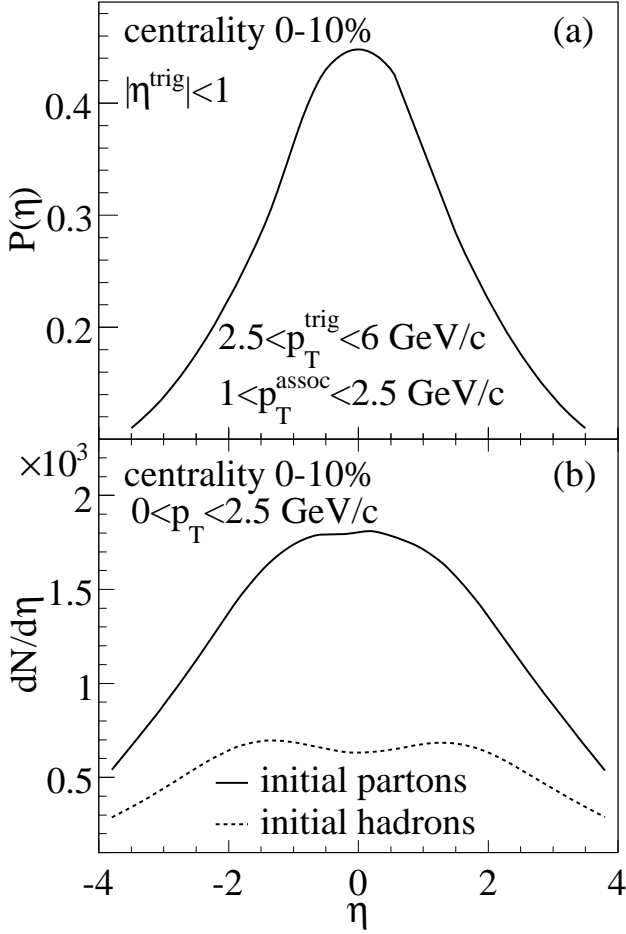


FIG. 6: AMPT model calculations in Au + Au collisions (0-10%) at $\sqrt{s_{NN}} = 200$ GeV. (a): conditional probability $P(\eta)$ to find the away side associated parton ($1 < p_T^{assoc} < 2.5 \text{ GeV}/c$) at pseudorapidity η if the trigger parton ($2.5 < p_T^{trig} < 6 \text{ GeV}/c$) is found at $|\eta^{trig}| < 1$ in the initial state of melting AMPT model; (b): the pseudorapidity distribution of initial partons (hadrons) ($0 < p_T < 2.5 \text{ GeV}/c$) before parton cascade (hadronic rescattering). solid: η distribution of initial partons in the melting AMPT model; dash: η distribution of initial hadrons in the default AMPT model.

AMPT model, but there is no distinct difference between the two cases in the melting AMPT model with/without hadronic rescattering. It is interesting that the associated away-side yields in the melting AMPT model can be extended to high pseudorapidity region ($|\eta| > 4$), but those in the default AMPT model are confined within the region $|\eta| < 4$, which indicates that the medium at high pseudorapidity can be waked by an away-side jet due to strong parton interactions.

In panel (a) of Figure 6, it shows the conditional probability $P(\eta)$ to find the away side associated parton ($1 < p_T^{assoc} < 2.5 \text{ GeV}/c$) at some pseudorapidity η , if a trigger parton ($2.5 < p_T^{trig} < 6 \text{ GeV}/c$) is found

at $|\eta^{trig}| < 1$ in the initial state before parton cascade, which is consistent with the LO pQCD calculations [22]. It means that the away-jet is with a certain possibility to be in non-mid-pseudorapidity. At the same time, the pseudorapidity (η) distribution of initial partons (hadrons) ($0 < p_T < 2.5 \text{ GeV}/c$) before parton cascade (hadronic rescattering) is also presented in panel (b) of Figure 6. Since η distribution of particle number is proportional to the η distribution of energy density, the interactions between away side jets and associated particles should be more violent in mid-pseudorapidity region than in high $|\eta|$ region. In our previous work [25], the formation of partonic ‘Mach-like’ shock waves stems from strong parton cascade, therefore the η^{assoc} dependence of splitting parameter is expected to result from different violent degrees of jet-medium interactions in the medium which has different energy densities in the longitudinal direction. From Figure 5 (a) and (b), the η^{assoc} dependence of the splitting parameter can identify the partonic or hadronic origin of the Mach-like behavior, and provide the information about minijet production mechanism and the formed matter density distribution in the longitudinal direction.

In conclusion, the properties of partonic ‘Mach-like’ shock waves, including p_T^{assoc} and η^{assoc} dependences, have been investigated in the framework of a hybrid dynamical transport model which consists of two dynamical processes, namely parton cascade and hadronic rescattering. It was found that the splitting parameter D increases slightly with the transverse momentum of associated hadrons, which results from different interaction-lengths/numbers between wave partons and medium in strong parton cascade. On the other hand, the pseudorapidity dependence of splitting parameter D induced by a mid-pseudorapidity trigger hadron keeps almost a constant in mid-pseudorapidity region but drops rapidly in higher pseudorapidity region, which is on account of different strength of jet-medium interactions in the medium which has different energy densities in the longitudinal direction. Therefore, the correlative researches on the properties (p_T and η dependences) of ‘Mach-like’ correlation can provide a potential tool to explore the characters of both partonic and hadronic interactions in the formed matter at RHIC.

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